PUMPED STORAGE PLANT

ALSO

'FFESTINIOG'

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PUMPED STORAGE

THE demand for electrical power varies according to the time of day and the season of the year, being least at night and highest at a certain time of day and in the evening, particularly during the winter. At night, surplus power will be available unless generation is reduced, but nuclear and large modern thermal plant is operated most efficiently at continuous maximum output. On the other hand, hydro-electric plant can be started up and put on the line in a matter of minutes, and standby losses are therefore avoided. Hydro-electric generation is thus the best method for supplying peak loads, provided the scheme has been designed for this purpose. Water turbines are also much easier to regulate in accordance with demand than steam sets. At the same time, a full storage reservoir, ready to be used at any moment, provides ideal standby capacity.

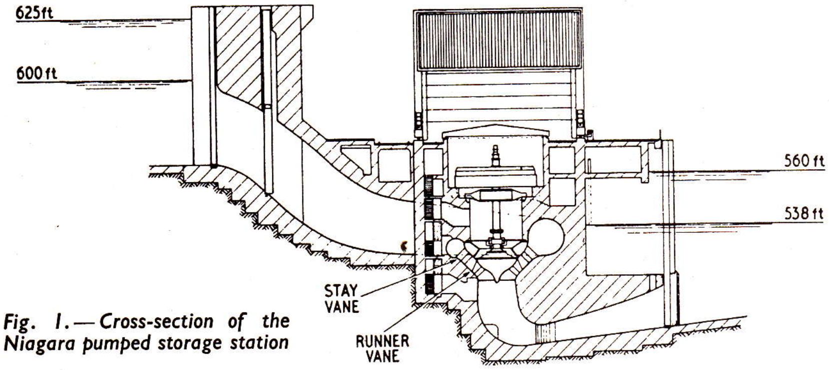


Fig. 1.—Cross-section of the Niagara pumped storage station

By using surplus generating capacity during the night, pumped storage plants can be used to flatten the demand variations by pumping at night and generating during peak periods in the day. However, pumped storage is economical on a large scale only when cheap base-load energy is regularly available. An analysis of pumped storage economics was given by Dr. Charles Jaeger in an article on the "Future of Pumped Storage" in the *Electrical Review* of 25th December, 1959.

The classical arrangement of a pumped storage plant is a lower and an upper reservoir for daily storage and a power station with units, each consisting of a motor/generator, a turbine and a pump. The pump is connected to the motor/generator either by a mechanical coupling, which can be engaged or disengaged only when the set is stationary, or by a hydraulic coupling if it is necessary to change the duty immediately without disconnecting from the line and stopping. The first arrangement is the more common because there is usually a sufficient interval between the generating peaks and the pumping periods.

When generating, the pump is uncoupled to reduce losses and, when pumping, it is connected to the unit and is run up by the turbine and synchronised. The water supply to the turbine is then cut off and the machine is dewatered so that the turbine runner will rotate in compressed air with the minimum loss. Thus, starting up for pumping creates no electrical problems.

The reservoirs are designed only for daily storage plus a reserve and they are therefore much smaller than those for a normal hydro-electric scheme. Civil works are thus substantially cheaper and the overall cost per kilowatt can be as low as one-third of the figure for the normal hydro-electric development (i.e. about £50/kW). This means that the cost of the pumped storage machinery is a much larger percentage of the total and the development may stand or fall economically according to the cost of this machinery. Hence, a considerable effort is being directed towards combining the pump and the turbine into a single reversible machine which will pump efficiently when rotated in one direction and will generate efficiently when running in reverse.

Reversible Pump/Turbines

The lower the operating head, the larger are the physical dimensions of hydro-electric machinery. In fact, the three-machine solution for pumped storage plant cannot be economically adopted for low head sites. Until the

Fig. 2.—The Niagara Deriaz runner at the works, with the vanes open

PLANT

By M. BRAIKEVITCH, M.I.Mech.E., A.C.G.I., D.I.C.*

PROGRESS IN DEVELOPING REVERSIBLE PUMP/TURBINES

Peak loads can be economically supplied by carefully designed hydro-electric schemes and, by pumping during the night, pumped storage plants can absorb surplus energy from base-load plants. To utilise low head sites and build higher head schemes more cheaply, intensive development is being undertaken in an effort to combine the pump and turbine into a single reversible machine

development of a large economical reversible machine several years ago, no low head sites could be used for pumped storage.

Tubular turbines which have now been developed could be used for very low head pumped storage schemes and Deriaz machines have been used under higher head conditions. Recently, Deriaz machines have been designed and are being manufactured for a medium head site while, for high heads, reversible Francis machines are being developed.

Units with separate pumps and turbines have the advantage that both pump and turbine can be individually designed for optimum efficiency and, when pumping is required, the set can be started by the turbine. Ideally, a single reversible machine would require a 10 to 20 per cent increase in speed when changing from generating to pumping if the wheel is to operate at maximum efficiency in both directions. This would require a two-speed generator/motor and one such plant has actually been built at the Flatiron station in the U.S.A. (see the article by Dr. J. H. Walker in the *Electrical Review* of 9th October, 1959, entitled "Generator/Motor Problems"). Dual-speed electrical machines are complicated and costly and therefore reversible waterwheel design is aimed at reducing the losses both when pumping and "turbining" so that the difference in optimum speeds is reduced to the minimum. A further disadvantage with reversible machines is that, when acting as a pump, the machine has to be started electrically. However, reversible machines provide a more economical solution for pumped storage than separate turbines and pumps.

Deriaz Machines

Since it is not practicable to employ a separate pump and turbine for low head sites, the first reversible machines were designed in Great Britain for this range. These Deriaz turbines were for the pumped storage station at Niagara and they were manufactured in Canada. The operating head is from 60 to 90ft and the output of each of the six units as a turbine is 48,000 b.h.p. while, when pumping, each can deliver 4,900 cusecs at 92·3 r.p.m. This turbine was invented by Mr. P. Deriaz, chief water turbine designer of The English Electric Co.,

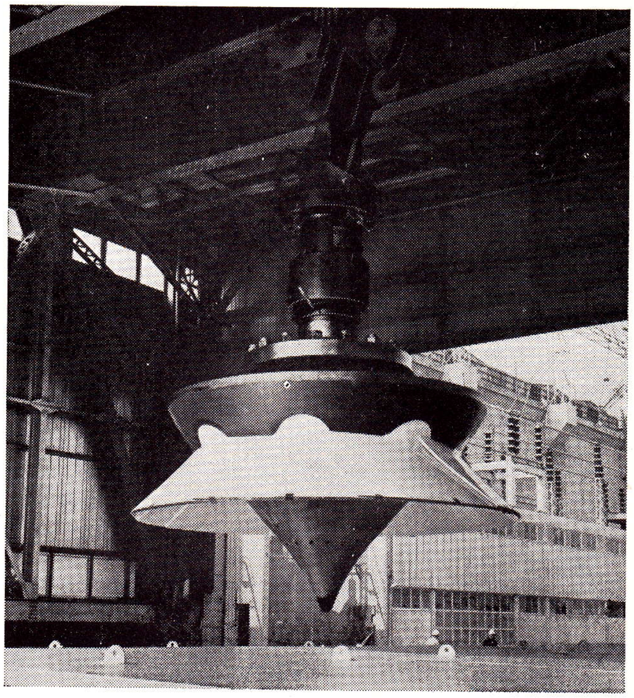
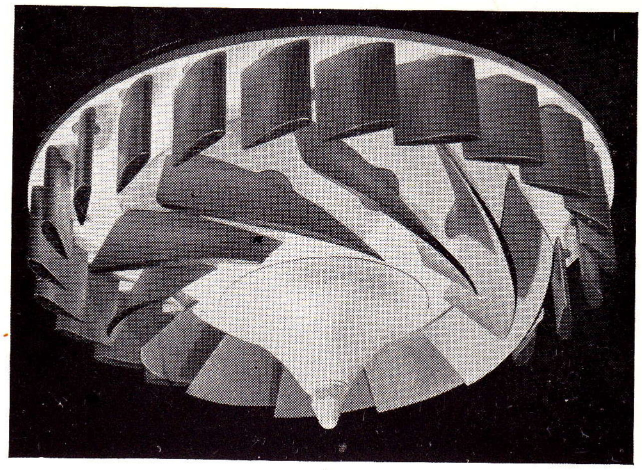


Fig. 3.—The Niagara Deriaz runner at site, with the vanes closed

Fig. 4.—Design of guide and runner vanes for Valdecanas



* The English Electric Co., Ltd.

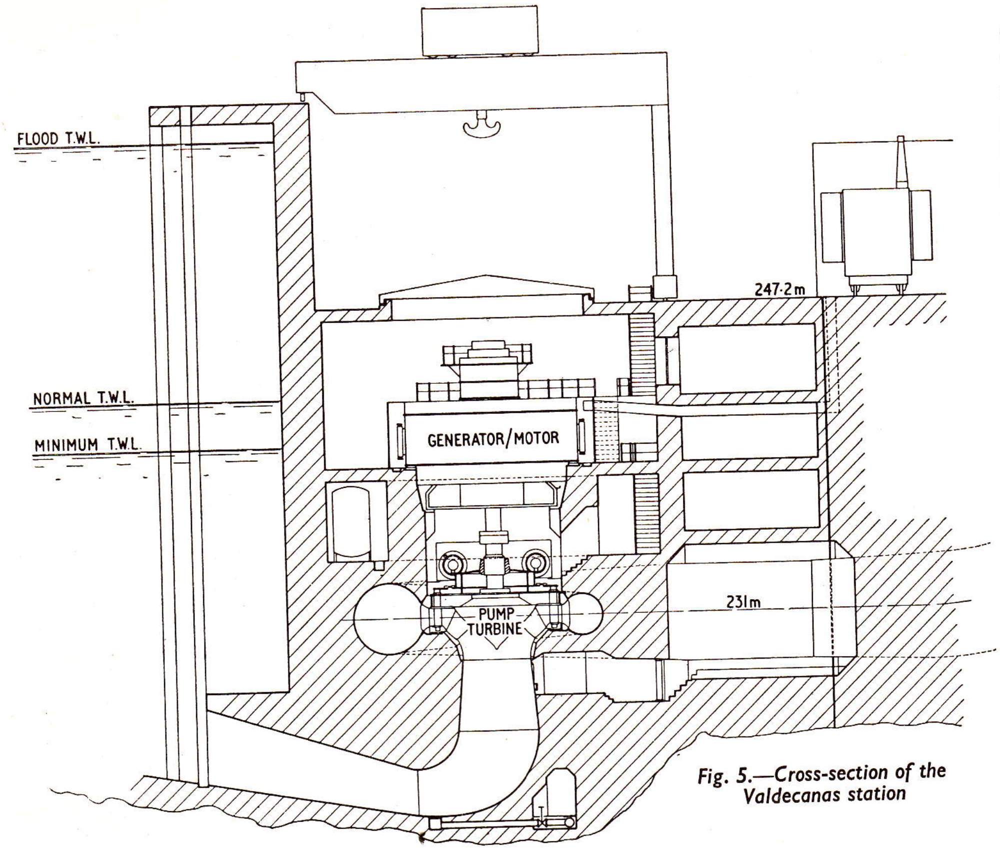


Fig. 5.—Cross-section of the Valdecanas station

Ltd., to provide a machine operating under heads in excess of 200ft which would have the flat efficiency/load characteristics as well as the part-gate stability of operation of the Kaplan turbine. It was then found to have great possibilities as a pump/turbine for heads both above and below the original range. An article comparing the Deriaz and Kaplan turbines was published in the *Electrical Review* issue of 13th November, 1959.

Fig. 6.—Deriaz turbine model for Valdecanas with torque measuring gear at the 'English Electric' laboratory, Rugby

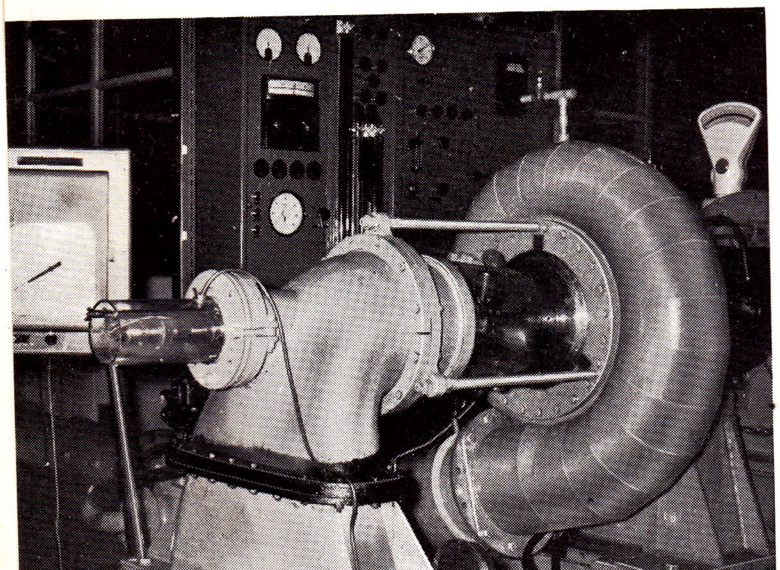


Fig. 1 is a cross-section of the Niagara plant. It will be noted that the speed-ring/spiral-casing assembly of welded steel plate is arranged as a direct extension of the mixed-flow runner so as to avoid changing the direction of the issuing water when pumping and so gain in efficiency. Since the output is governed by the opening of the runner vanes, and the latter can close completely to prevent the passage of water at standstill, no guide vanes were used. Instead, to increase the turbine output at low heads, each stay vane was fitted with a movable flap (rather on the lines of an aeroplane wing), this being a cheaper arrangement. Fig. 2 shows the assembled runner in the works with the vanes opened; in Fig. 3, taken on site, they are closed. The vanes are of steel with welded-on stainless steel protection; they are set in a cast steel hub and operated by an oil pressure servo-motor. The overall diameter of the runner is 22ft.

A reversible unit has to be run up by the motor/generator to start pumping, so a reduction of the starting torque is of great importance. This can be achieved by completely closing the vanes of the Deriaz runner to approximate to a continuous conical surface which glides easily through the water so that the motor can start rotating the unit without difficulty. In fact, the same method is adopted for starting as a turbine, the generator acting as a motor, and once the machine is on the line the vanes are opened to give power.

A feature which should be noted is that the quantity pumped can be varied in the same way as the turbine output by operating the runner vanes. Thus, the pump input can be varied to suit the surplus of energy available so that, in fact, both when operating as a turbine and when pumping, such a unit could be governed by the peak-load requirements and so keep the output of the thermal plant at a steady value.

The next step was to go to a higher head, namely, 250ft at Valdecanas on the River Tagus in Spain, for which station Britain is supplying 115,000 b.h.p. reversible Deriaz units. Since the head drops seasonally down to 160ft and it is desirable to generate the maximum peak load at all times, a conventional gate apparatus is being fitted. The speed is 150 r.p.m. Fig. 4 shows the runner with its movable vanes surrounded by the movable guide vanes. The combination of the two movements allows the best vane angles and best efficiency to be obtained over the wide operating range. Again, the pump input can be varied to suit the surplus available so that the energy need not be absorbed in rigid blocks

corresponding to a multiple of one unit, but can be changed gradually. Fig. 5 is a diagrammatic power station arrangement showing that, apart from the deeper machine submergence required for the pumping duty, this does not differ from the usual turbine layout.

When pumping, the guide vanes receive the flow from the impeller and can be subjected to fairly large and varying forces. Considerable forces are also exerted on the impeller vanes. Fig. 6 shows a Valdecanas model in the laboratory fitted with gear for accurate measurement of the vane torques under all operating conditions. The measurement is electrical, based on the Wheatstone bridge principle, and shows up the transients. During pumping, the guide vanes are locked individually by oil pressure in the selected position. The runner has stainless steel vanes, part of the envelope is lined with stainless steel, and the arrangement of the gate apparatus and the speed-ring/spiral-casing assembly follows conventional-turbine practice.

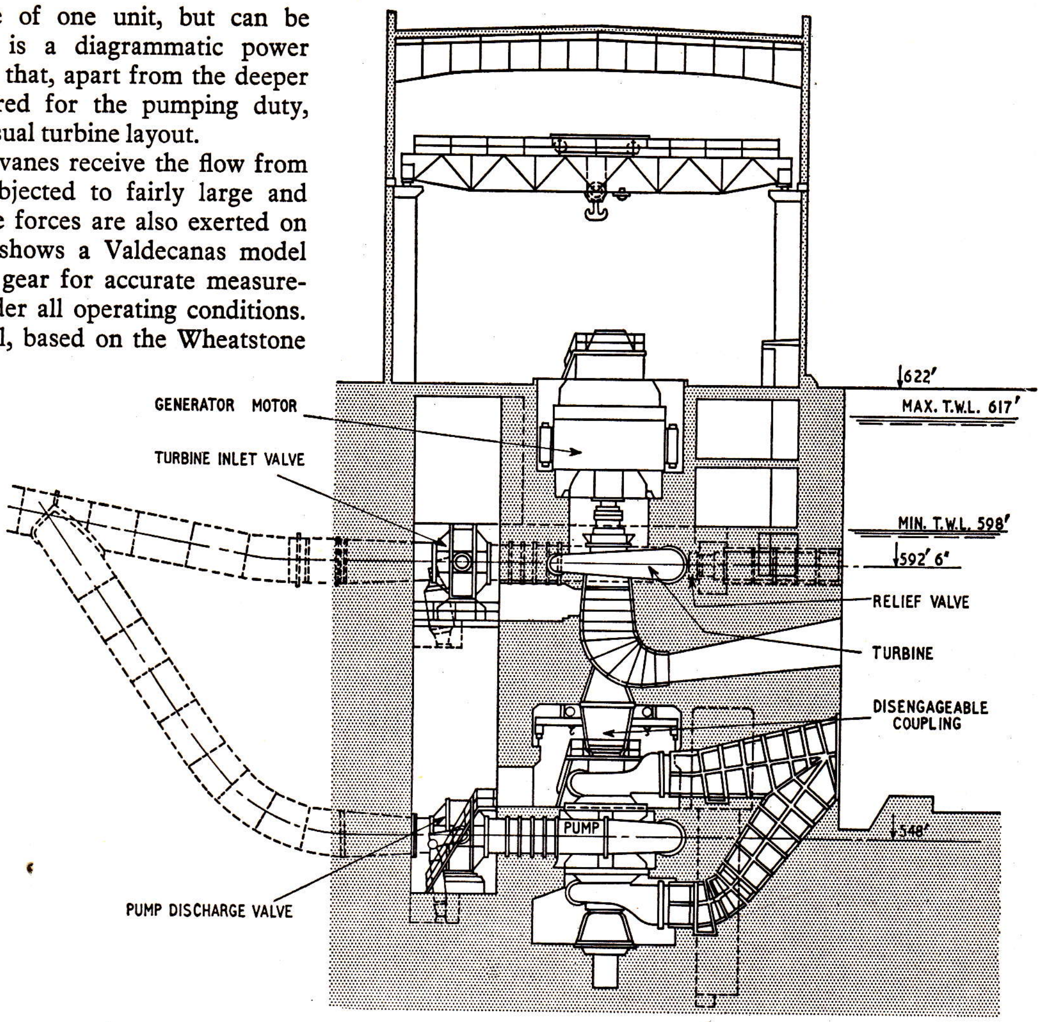


Fig. 7.—Section through Ffestiniog pumped storage station

Francis Machines

When the Ffestiniog scheme was designed, it was decided to employ separate pumps and turbines because the head was high (1,000ft) and, at that time, no fully developed reversible machine was available. It was also the first large pumped storage scheme to be undertaken in this country and, as such, it was felt that the design and use of reversible machines would be premature. However, the Loch Awe scheme in Scotland, at which site work has just commenced, may employ reversible machines. The features of the Ffestiniog site are so favourable that the extra expense of a three-unit set will not make the project uneconomic.

Fig. 7 shows the arrangement at Ffestiniog as adopted, and Fig. 8 is a possible equivalent layout with a reversible pump/turbine. It will be noted that the pump/turbine occupies the place of the original pump so as to obtain the necessary submergence for this layout. Fig. 9 depicts a model of the turbine runner which will be used, and Fig. 10 shows a reversible pump/turbine wheel for about the same duty. The main difference between the two wheels is that for pumping a much longer vane is required to build up the pressure gradually, whereas for the turbine a shorter vane can deal with the same head. (Conversion of pressure to velocity of water through a turbine is comparatively easy, but conversion of velocity to pressure in a pump is always difficult.) Hence, while the inlet pumping diameter of the reversible runner is the same as the outlet diameter of the turbine, the outlet pumping diameter of Fig. 10 is larger than the inlet diameter of the turbine in Fig. 9.

Extensive laboratory tests have been made in Britain,

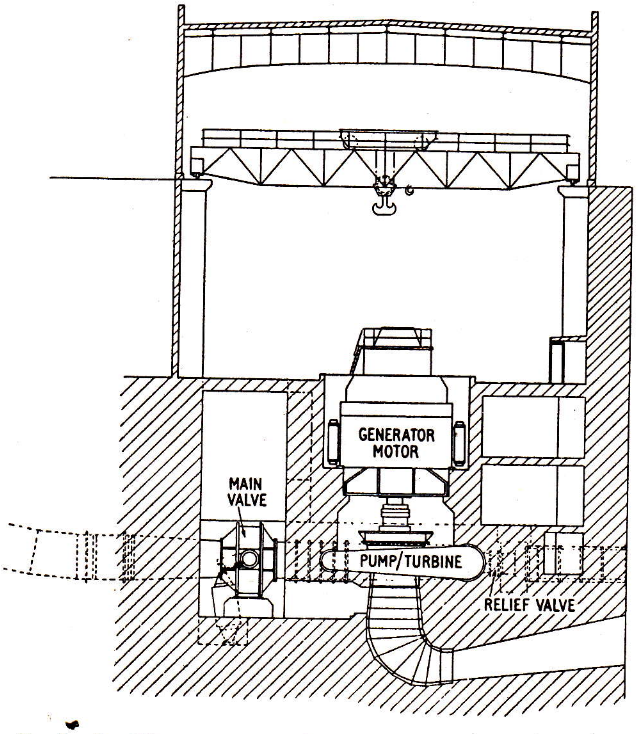


Fig. 8.—Possible arrangement of a reversible installation based on the Ffestiniog site

and full-size *high head storage pumps have* been run successfully in reverse as turbines, so the necessary data for extending reversible machine design to the really high heads are, in fact, available. The monetary gain on the machinery would be substantial, for 40 per cent could be saved by using reversible machines instead of separate pumps and turbines.

The siting of power stations with reversible machines would be governed by the pumping duty so that in the case of overground stations deep excavation would still be required to obtain the necessary submergence, but the building height would be very much less. The gain would be greatest for an underground station where the reduction in the volume of the excavated building is considerable while the placing of the station at a lower level to get submergence only means lowering the station cave bodily so that the excavation would not be greater. A small additional cost is a slight deepening of the pressure shaft feeding the station.

With the fixed vane reversible runner of Fig. 10, starting for pumping will be more difficult than with a Deriaz machine because the vanes cannot be closed to form a cone. A greater starting torque would be required, but this can be reduced by expelling the water by compressed air and running the wheel up to speed in air. Once the motor is on line, the air is exhausted and pumping begins.

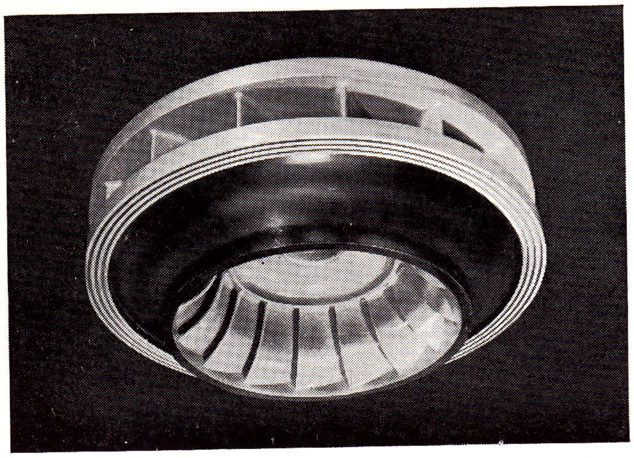


Fig. 9.—A high-head Francis turbine runner model

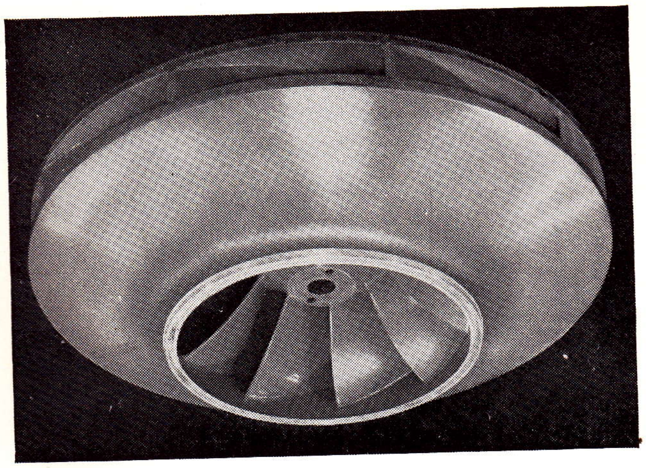


Fig. 10.—A high-head reversible Francis pump-turbine runner model to the same scale as Fig. 9

Regarding future developments, two extremes are possible. The first is to have the cheapest unit based predominantly on pump practice which uses a diffuser with fixed vanes instead of a gate apparatus. Power regulation is then not possible, the station being able to supply load only in multiples of the unit capacity and so dealing with what is virtually the base of the peak load with conventional hydro-electric plants doing the regulation. Similarly, when pumping, surplus energy from the system can only be accepted in steps, each step equal to the power of a unit, and it is necessary to start up or shut down units to pass from one step to the next.

The second solution is to follow turbine practice, having a movable gate apparatus so that the turbines can govern and follow the peaks. During pumping, energy can still only be accepted in blocks, because the turbine guide vanes, being situated at the outlet of the runner when pumping, cannot vary the discharge effectively. Further development of the second solution is to include movable runner vanes, as the Deriaz machine for Valdecanas, when a very flat efficiency curve combined with overload capacity is obtained for the turbine and the pump discharge is variable. For the lower heads, the Niagara solution, which has no guide vanes and relies on the movable runner vanes of the Deriaz machine, gives a fairly similar result.

In Britain, where the bulk of the power comes from large thermal and nuclear stations, the fully developed second solution seems the better choice because the reversible hydro stations will ultimately be able to do all the regulation both during peaks and at night during the pumping cycle, simplifying the operation of the base-load plant and allowing it to work most efficiently and economically.

To conclude, it may be mentioned that, as Great Britain relies ultimately on very large thermal stations and on nuclear plant, interest in pumped storage was stimulated in this country as this was necessary to make a large unit programme really economical. This, in its turn, put Britain in a leading position to design and supply reversible turbine plant (the total of such plant dealt with to date is 633,000 b.h.p.) so that, in fact, steam development helped hydro development.

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FFESTINIOG

£15 MILLION 300 MW DAILY PUMPED STORAGE SCHEME

The first of the four 75 MW sets at the largest pumped storage scheme in the world is to be commissioned next year and, in 1963, the whole project will be operating. Each vertical set comprises an alternator/motor and turbine together with a separate pump and a disengageable coupling between the pump and turbine. Automatic stopping and starting equipment will also be installed as well as comprehensive protection and alarm devices

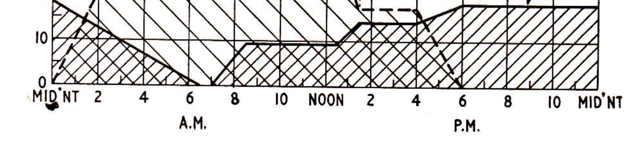
INVESTIGATION into the possibilities of pumped storage in the national electricity supply system commenced in 1948. Detailed studies of various alternatives showed that the Ffestiniog scheme in Merioneth, North Wales, was technically the most attractive. In 1955, statutory authorisation to proceed with the scheme was obtained and site work commenced in April, 1957. The photographic illustrations, taken by a staff photographer, show the state of construction on 26th January, 1960. The first set is scheduled for commissioning in August, 1961, followed by the other three sets at approximately six-month intervals.

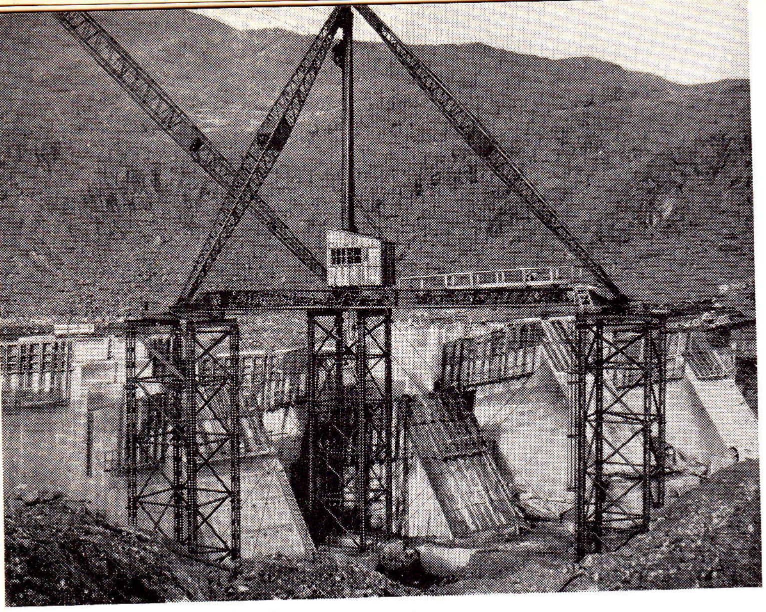
Preliminary studies into the possibilities of storage schemes in Britain indicated that the most favourable conditions would be obtained if pumping were done between midnight and 6.30 a.m. A consideration of the characteristics of the plant, which included an assumed overall efficiency of 67 per cent, indicated that the generation period should be between 4 and 4½ hours per day. This would be sufficient to cover the system peaks, and Fig. 1 shows a possible operating régime to meet the requirements.

Since the maximum storage capacity of the Ffestiniog project was limited by site conditions to approximately

Title picture shows: View from the tunnel portal looking east. The excavations for two penstocks can be seen leading to the power station. The Tan-y-Grisiau dam can be seen in the middle distance. The lower reservoir will cover the ground between the power station and the dam at present occupied by the Ystradau stream

Fig. 1.—Possible daily load cycle showing variations in the water level of both upper and lower reservoirs and the pumping and generating periods. The generating periods, at times of peak load, will vary from day to day depending on weather conditions, day of the week, time of the year, etc.





Stwlan dam forming the upper reservoir

60 million cu ft, corresponding to a daily station output of about 1·2 million kWh, the maximum generating capacity for the site was fixed at 300 MW, assuming a 4-4½ hr daily generating period.

In addition, the station is intended to act as a reserve capacity to meet abnormal plant breakdowns elsewhere in the system. This duty will enable substantial savings to be made in standby fuel costs which would otherwise be required to maintain boilers up to pressure. It is estimated that the use of pumped storage for this purpose will probably involve operation equivalent to 700 hr of full load output per annum.

The gross annual generation is thus expected to be about 300 million kWh with a corresponding annual load factor of 11·4 per cent. The installed capacity of an equivalent coal-fired plant was calculated to be about 360 MW. This calculation has led to the postponement of two 60 MW and two 120 MW units programmed for installation in two stations in North-West England near the Ffestiniog scheme.

The total capital cost of the Ffestiniog pumped storage project, including transmission, is estimated at £15 million. This compares with an estimate of £25 million for an equivalent steam plant. During the first year of full operation, the estimated saving in annual running costs by the use of pumped storage as against steam plant is £207,000.

General Description

The general layout of the scheme can be seen from the relief map on the pull-out supplement. The scheme can generally be divided into four sections:—The upper reservoir, the pressure conduit system, the power station and the lower reservoir. It will be noted that a surge shaft has not been incorporated because of the unsuitable topography and the good head-length ratio of the site, but relief valves have, of course, been fitted to the turbines.

Upper Reservoir

The upper reservoir is being formed by raising the water level of Llyn Stwlan from 1,580ft to a top water level of 1,648ft by a 900ft-long buttress dam 118ft high. The normal operational maximum daily rise and fall of the water level will be 65·5ft. Stwlan dam will incorporate gravity sections at the east and west flanks with a gravity spillway on the west flank. The 800ft massive buttress section will have buttresses spaced at 50ft centres with a minimum thickness of 15ft, while the downstream face of the walls between the buttresses will be in the form of horizontal ellipses with minimum thickness of 12ft.

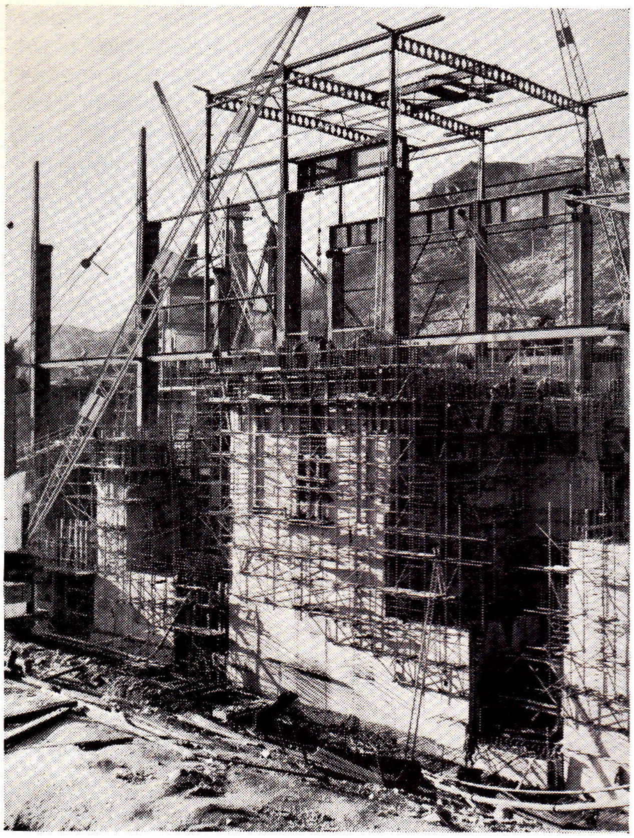
The spillway section will discharge any overflow to the stream below the dam. Level relays will be installed to ensure that pumping is stopped when the upper reservoir is full, since the stream cannot carry the full pumping discharge of 3,000 cusec. The normal reservoir draw-off to the stream will consist of a 3ft diameter steel pipe fitted with a sluice valve at the inlet and a discharge regulator at the outlet, a small valve being provided for normal compensation water flow. The natural catchment for the upper reservoir is 165 acres and the average rainfall is 120in per annum. This small catchment will make a contribution of only 4 million kWh to the total annual output.

Pressure Conduit System

Two intakes are being provided approximately 60ft upstream from the dam; they consist of two 14ft 6in diameter vertical shafts 680ft deep. The intakes will incorporate 14ft 6in square motor-wound Stoney gates designed for gravity closure. Fixed screens and maintenance bulkheads will be installed upstream of the gates. The gates will be opened under balanced conditions after the flooding of the shaft through a by-pass valve.

Each of the two vertical concrete-lined shafts will bifurcate at the bottom into tunnels, approximately 10ft

Stwlan dam looking south from the crest level and showing excavations for buttresses 7 to 13



The power station from the north-east showing the downstream face. Nos. 1, 2 and 3 storage pump inlets can be seen at the base of the station

in diameter and about 3,800ft long. This arrangement allows for two tunnels and one shaft to be drained for inspection and maintenance while the machines supplied from the other two tunnels are operating. For about 1,800ft upstream of the tunnel portal, the tunnels will have welded steel linings surrounded by concrete giving an internal diameter of 9ft 5in; the remaining 1,950ft of each tunnel to the bifurcations at the base of the shaft will be lined with 18in of concrete giving an internal diameter of 10ft 8in.

The four tunnels emerge about 200ft above the power station level at a portal chamber where dismantling pipes are being provided for access to the tunnels and penstocks. The welded notch ductile steel penstocks will be 7ft 6in in diameter and about 660ft long. Due to the short length of pipes, anchor blocks are required only at the top and bottom. The penstock and its pre-stressed concrete surround will be laid in a trench which will be covered with soil and grassed.

Each pipeline will bifurcate behind the power station, the upper branch being connected to the turbine inlet and the lower branch to the pump discharge. These pipes will be surrounded by mass concrete in a thrust block immediately adjacent to the upstream wall of the station.

Lower Reservoir

The lower reservoir is being formed by building a concrete gravity dam across the natural basin of the Afon Ystradau, near the village of Tan-y-Grisiau. The dam will be 40ft high and about 1,800ft long, and the normal operational daily rise and fall of the water level will be 18ft. This reservoir has a natural catchment area of 2,350 acres and the average rainfall is 90in per annum.

The spoil from the excavation for dam foundations will be used to conceal a considerable length of the downstream face of the dam.

Power Station

The power station is situated on the west bank of the lower reservoir and will contain four 75 MW alternator/motor-turbine-pump vertical sets. (The possible use of reversible pump/turbines for high head sites is discussed in the previous article, with particular reference to Ffestiniog.) The site is within the area of the Snowdonia National Park, and many authorities, including the Royal Fine Art Commission, were consulted in the design stage. The architects' perspective, showing the power station in relation to the landscape, was exhibited at the Royal Academy in 1958. The walls of the power station will be faced with natural stone, the large expanse of which will give a powerful yet restrained character to the building in consonance with its environment. The glazing at high level affords a contrasting lighter element and, internally, will act as a "lantern" with good light reflection from the ceiling. A feature will be made of the viewing windows overlooking the reservoir.

The excavation for the power station is about 80ft deep by 80ft wide and 250ft long, while the total height of the power station, including the basement areas, will be about 160ft. Reference to the graphic illustration in the pull-out supplement shows that the station has four main floors, these being the pump basement, the pump floor, the turbine floor and the operating floor.

Between each pair of machines is a large pump dismantling pit extending from the operating floor down to the pump basement. This will enable the two main power station cranes to handle pump components to the lowest levels. These two identical electric overhead travelling cranes, which are being supplied by Cowans,

Llyn Stwlan. The water level of this lake will be raised about 70ft by the buttress dam to form the upper reservoir

Sheldon & Co., Ltd., Carlisle, are suitable for precise handling with cross-traverse and long-travel motions capable of positioning loads to within about $\frac{1}{4}$in. Each crane has a span of 50ft 1in with a 120 ton main hoist and a 30 ton auxiliary hoist. When coupled together, the two cranes are capable of handling a gross load of 240 tons (each generator rotor weighs 210 tons), the main blocks being connected by a 24ft long lifting beam, which is being supplied by Sir William Arrol & Co., Ltd.

Two cranes for each half of the station are also being supplied for the pump floor level. Each of these cranes has two 10 ton capacity crabs so that the maximum pump-erection lift of 40 tons can be handled. Air-conditioning plant will also be installed in the power station to keep the air moving in the lower levels.

The plan of the station at operating floor level is shown in Fig. 2. Transformers and switchgear will be sited behind the station, while the control room will be at one end and the other end will contain an annexe for office accommodation.

Turbines

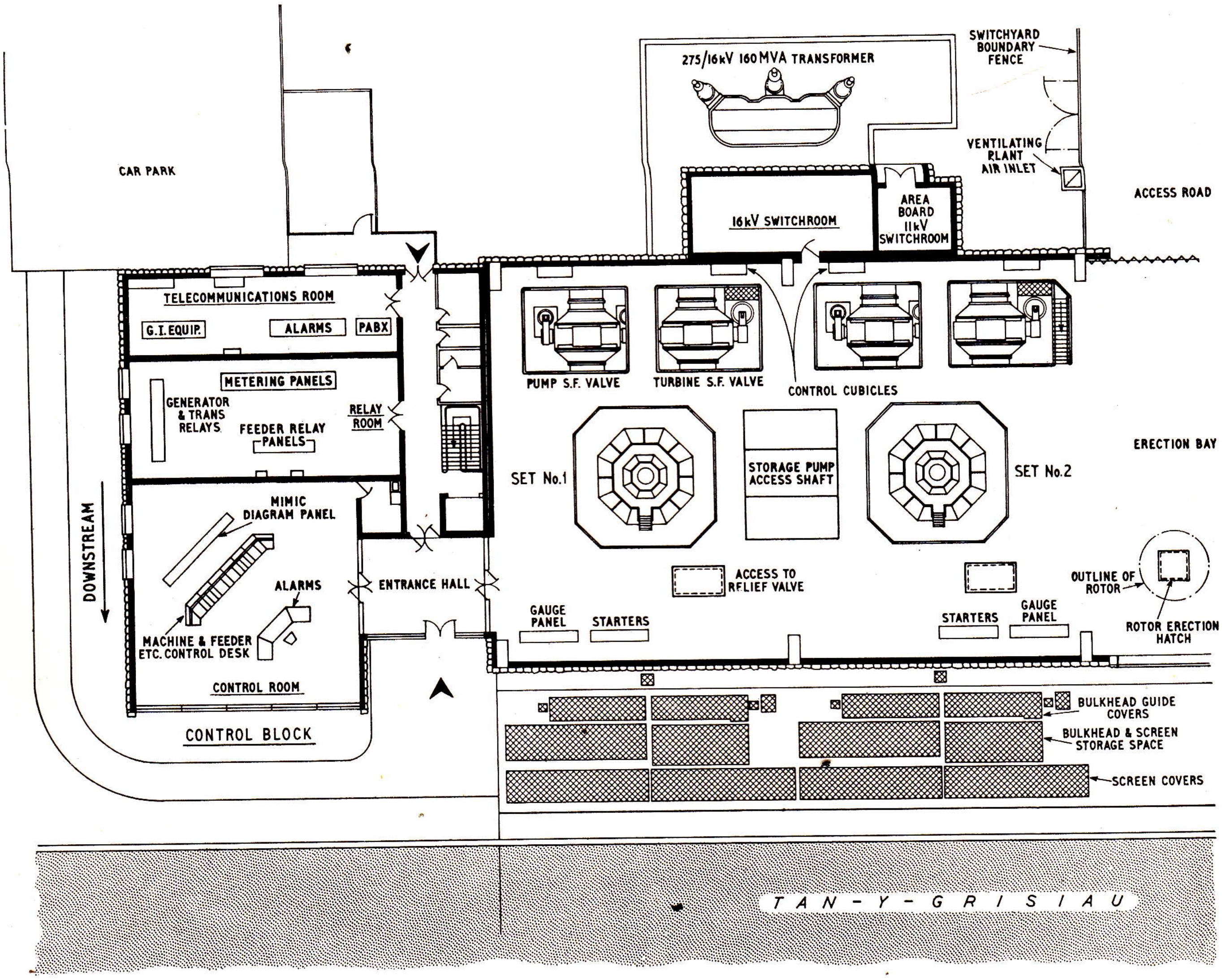
The 'English Electric' vertical shaft Francis turbines will operate at 428 r.p.m. and are designed to develop 105,000 h.p. over a head range of 925 to 1,020ft. The spiral casings are of welded plate lobster back construction with a cast steel stay-ring and have been constructed in two halves for bolting together on site. The turbine runners are of cast stainless steel (13 per cent chrome) with an outlet diameter of 74in with labyrinth seals. They are mounted on forged steel shafts with self-lubricating upper bearings, while the lower bearing at the base of the draught tube is grease lubricated. The guide vanes are also of cast stainless steel.

Pumps

The Sulzer vertical two-stage double-inlet pumps are designed for a discharge of 745 cusec at 1,000ft head. The power required to operate the pump at rated discharge is 93,600 h.p. at the coupling (110,000 h.p. motor power). The main pump casings are of steel with welded steel volutes and the main suction end covers are of cast steel. There are two first-stage single- and one second-stage double-entry impellers. These have been cast from 13 per cent chrome steel. Each pump has two shell type pressure oil lubricated guide bearings, one housed in the upper suction cover and the other beneath the lower suction cover.

Shaft Bearings and Coupling

One of the two main thrust bearings will be situated between the alternator and the main exciter. This will



carry the weight of the top shaft, the alternator rotor and the turbine runners, and it will be able to withstand the hydraulic thrust on the turbine runner. The second thrust bearing, at the foot of the pump shaft, will carry the weight of the pump shaft and the rotating parts of the pump only, see Fig. 3. Since the pump has a double entry, the hydraulic thrust will be balanced.

The pump will be coupled to the main shaft by a toothed gear arrangement, see Fig. 4, engaged mechanically by oil pressure supplied by a pump in the basement and applied through the hollow pump shaft. Since it was decided that the complication of a clutch capable of engagement at speed was not justified, the pumps will be coupled to and uncoupled from the turbines only when the machines are shut down.

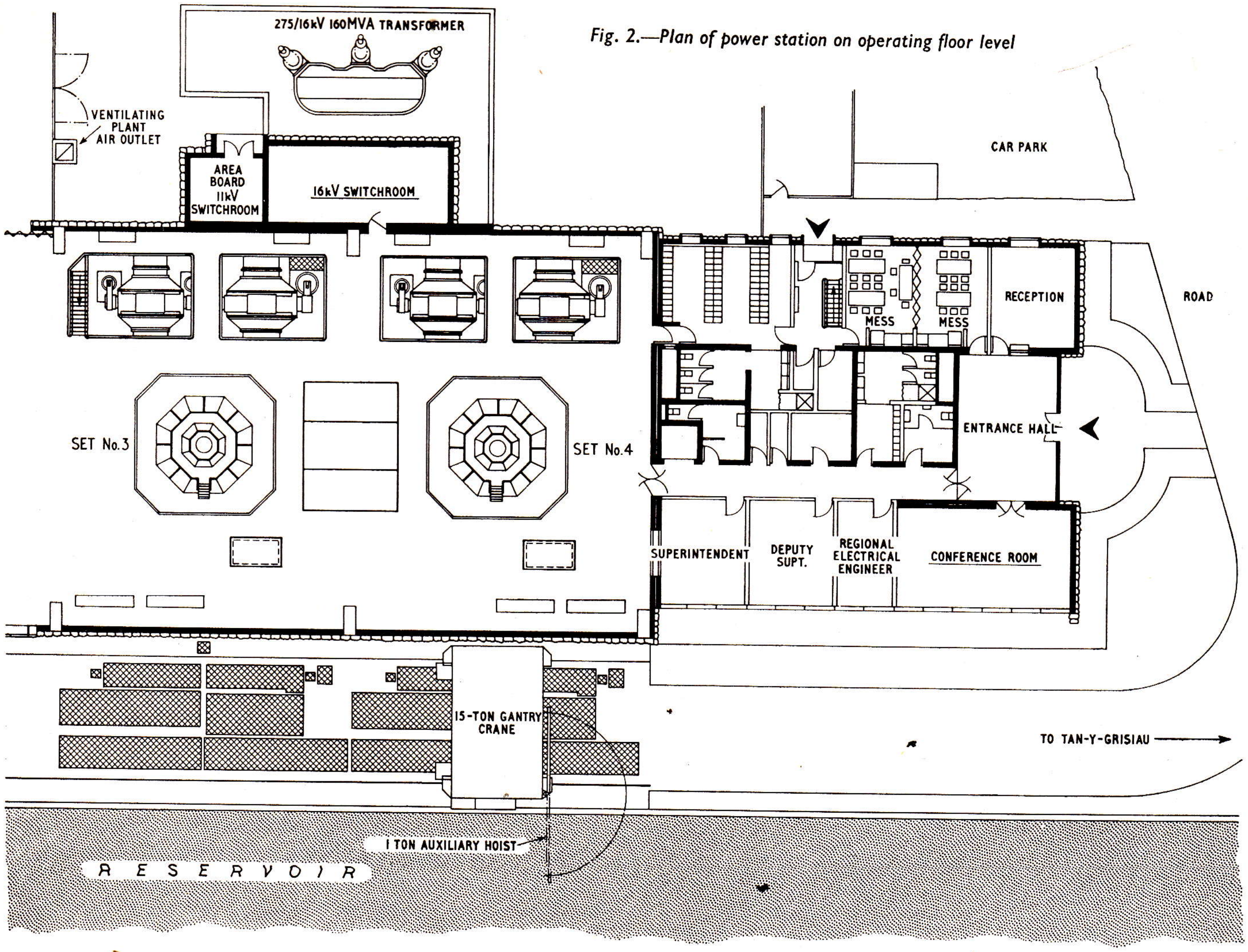
The pump coupling consists of an outer cylinder with 138 internal teeth, both at the bottom and at the top. The teeth at the lower end will be in constant engagement with the teeth on the pump shaft and the cylinder is designed to move upwards to engage the top teeth with those on the turbine shaft when pumping is required. The shape of the male and female teeth is identical and the ends of the toothed rings are chamfered to assist in engagement. The probability of direct engagement is about 91 per cent. If the coupling does not engage at the first attempt, the pump shaft will be rotated by a clamp on the shaft operated by a servo, see Fig. 4. The power oil for operating the coupling mechanism will be admitted to the underside of the piston situated at the top of the pump shaft. Oil pressure on the reverse side of this same piston will disengage the coupling after the locking device has been withdrawn. The oil pressure will be applied to this piston via a tube inside the hollow shaft. Oil for engagement will pass between the tube and the shaft and, upon disengagement, oil pressure will be applied via the tube.

Valves and Gates

The 'English Electric' "Straightflow" type turbine inlet valves have a diameter of 6ft and will be servo-motor operated by pipeline pressure water. The opening and closing times are 120 and 60 sec respectively. The pump discharge valve is of similar design with a diameter of 5ft 6in. When fully open, this type of valve presents a completely clear, smooth and straight water passage, while in the part-open position the deviation of the water stream is also sufficiently small to avoid most of the vibration usually associated with the unbalanced operation of valves.

Rapid governing without excessive pressure rise will be facilitated by the use of a 3ft diameter relief valve of

Fig. 2.—Plan of power station on operating floor level



the cylindrical balanced streamline type. The controls will be so arranged that the rapid closure of turbine gates cannot take place unless the relief valve is functioning.

Each of the four machines will have a complete set of gates and screens supplied by Sir William Arrol & Co., Ltd. These will comprise 14ft by 6ft 4in turbine relief valve bulkhead gates, 14ft by 8ft turbine outlet gates, 14ft by 12ft storage pump intake gates and two sets of screens, each 22ft by 18ft, fitted in front of each storage pump intake gate. The framing forming the gate seats and guides is being cast in a low nickel-chrome iron to resist corrosion. The gate seats are to be machined and faced with aluminium bronze and all parts of the castings which will be exposed to water are being shot blasted and sprayed with one coat of zinc and aluminium. The framing of each set is being assembled as a unit and the overall dimensions are approximately 67ft high by 34ft wide.

All the gates are of heavy welded steel fabrication with stainless steel facing strips instead of aluminium bronze, to avoid any tendency to seizure. Sealing of the gates will be by means of "music-note" seals on the top and sides of the gates with compression sealing on the bottom edge. Separate grooves are provided on the framing for each gate and are so arranged as to keep the gates and seals clear of the guides when lowering and carry them forward on to the seat at the end of travel. Provision is being made to ensure that each gate can only be inserted in its correct slot and an interlocking and warning system, utilising Castell keys, is incorporated to prevent the gates being lowered when the sets are in operation. The interlocking will also prevent the pumps and turbines being started until the gates are fully removed from the guides. All gates and embedded parts are to be machined and aligned to a close tolerance, as all four sets of gates are interchangeable. Nozzles will be provided at strategic points at the sill of each gate and high-pressure water can be forced on to the sills to clear any silt which may gather and prevent the gates closing properly.

Each of the two sets of screens in front of the pump intake gates will consist of three panels with horizontal and vertical bars. Aluminium bronze facing pieces will be fitted on each screen to facilitate guiding and removal. Instruments are to be provided to measure the head difference on each side of the screens and give visible and audible warning when the head difference reaches 1ft.

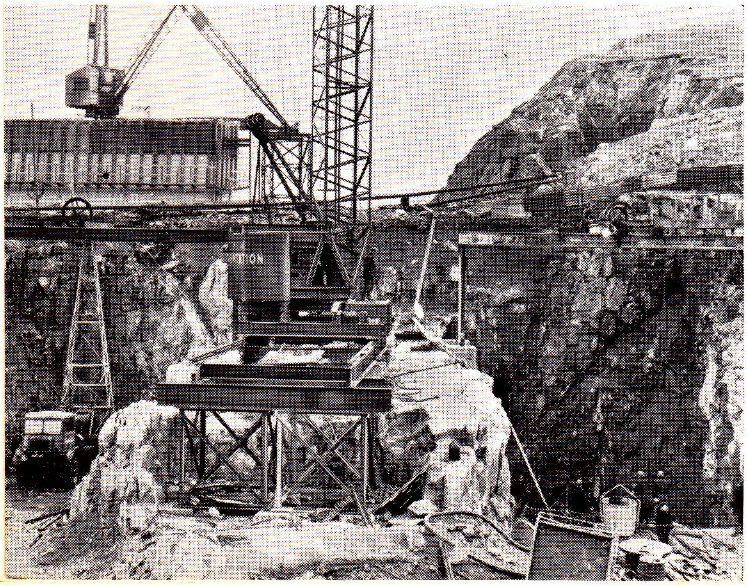
The space between the screens and the gates will be roofed over and a manually-operated flap will be incorporated in the turbine draught tube gate framing to allow the intake pump gate to pass. This flap will normally be lowered and arranged to give free discharge, but when either the intake pump gate or the draught tube gate is to be lowered, the flap can be retracted inside the line of the gates. Interlocking is also being provided on the flap operating gear.

A special lifting beam is being provided for lifting and lowering the gates and screens into place and provision is made on the beam for automatically engaging and disengaging. The 15 ton "Goliath" crane, which is designed for the insertion, withdrawal and transportation along the lower deck of all the gates and screens, is also being supplied by Sir William Arrol & Co., Ltd. The crane structure is of portal type and the main girders and legs are of welded box section. It will be capable of lifting a load of 15 tons at a rate of 10ft/min and travelling with it at a speed of 100ft/min or traversing at a speed of 10ft/min against a wind pressure of 10 lb/sq ft. It will also be capable of holding the dead load against a wind pressure of 30 lb/sq ft. An auxiliary jib complete with hand slewing gear and capable of handling a load of one ton will be incorporated to assist in clearing heavy floating debris in the way of the gates. All machinery will be covered by waterproof housings and the crane will be controlled from a cabin situated between the crane legs. Power will be supplied to the crane from a power plug and a cable reeling drum.

As much of the hydraulic machinery in the power station will be well below maximum tail-water level, a system of dewatering pumps will be provided.

Nos. 1, 2 and 3 tunnels at the portal

The two intakes under construction approximately 60ft upstream from the Stwlan dam



Motor/Generators

The four motor/generators being supplied by A.E.I. Ltd., Heavy Plant Division, are salient-pole synchronous machines, each rated at 78·9 MVA, 0·95 power factor, 16 kV, three-phase, 50 c/s. These machines are also

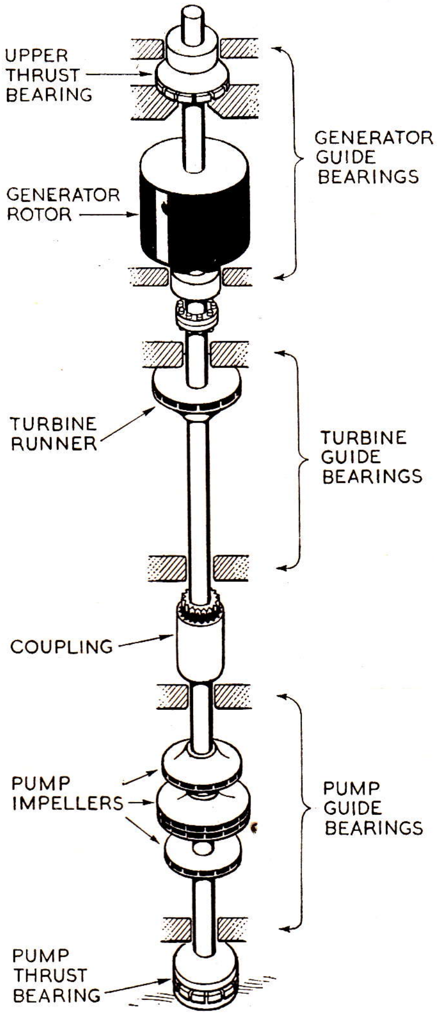


Fig. 3.—The main shafts, showing the bearings and the coupling. The total length of the shafts including the coupling is about 100ft. During erection, optical methods will be used to ensure accurate alignment

designed for operation as synchronous condensers. The rotor body is made up of steel discs, each about $3\frac{3}{8}$in thick, shrunk on to the shaft, and the poles are dovetailed into the 14 flats machined on the discs. Each machine will be air cooled and circulating fans are mounted at each end of the rotor. Four pairs of air/water heat exchangers will be provided for each machine for cooling this air. The thrust bearing, situated above the rotor, will be of the Michell type with centre-pivoted pads to guard against the possibility of reverse rotation if the motor supply is lost while pumping. In this event the pump discharge valve will be closed quickly, but this operation may not be quick enough to prevent the water at the pump discharge reversing its direction and that of the pump. Whether pumping or generating, all machines rotate in the same direction. This is to enable the turbine to start the pump and bring it up to speed for synchronising.

The main exciter and pilot exciter will be mounted above the main machine and will be direct driven. Two permanent magnet a.c. generators will be mounted above the exciters, one being used to supply the pendulum motor of the governor and the other to supply the speed-sensitive devices, for example, those controlling the operation of the brakes and connection of the automatic synchronising apparatus.

Electrical Connections

The output of each machine will be controlled by a 16 kV, 3,000 A, 1,500 MVA G.E.C. solenoid-operated oil circuit-breaker. Each pair of alternators will then be paralleled and connected to one of the two 160 MVA, 16/275 kV Ferranti OFW transformers. The h.v. side

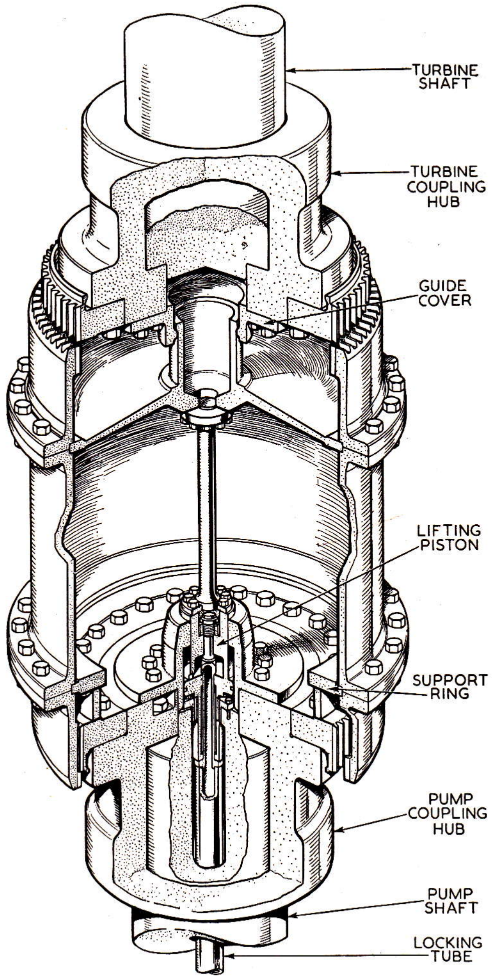
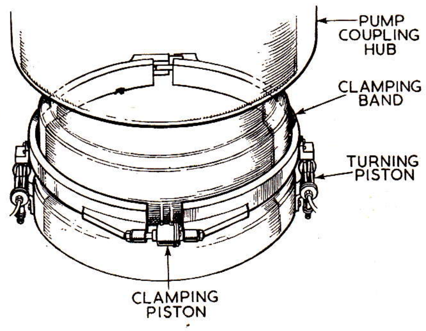


Fig. 4.—Details of the coupling. Power oil for raising the coupling to engage with the gear teeth on the bottom of the turbine shaft is admitted to the underside of the lifting piston via the annulus between the hollow pump shaft and the central tube. To disengage the coupling, oil pressure is applied through the locking tube to the top of the piston. The outside diameter of the coupling is approximately 5ft 6in



of each of these two transformers will be connected to a 275 kV line to Connah's Quay switching station. These lines will later be looped into Trawsfynydd switching station, which is now under construction to control the nuclear power station.

The 16 kV switchgear will be housed in two switching rooms, each of which will accommodate a suite of panels for a pair of sets. The panel for one pair of sets will consist of two 16 kV circuit-breakers with an interconnecting panel between these units forming the 6,000 A tee-off to the transformers. The connection from the machines to the switch unit will consist of three cables per phase while the connection from the switchgear to the transformers will consist of a single copper bar per phase from the centre unit of the switchgear to the low-voltage terminals of the transformer. These busbars will be screened by aluminium sheeting and will be supported on insulators.

The h.v. star point of the delta-star generator transformer will be directly earthed and each transformer will be connected to a 275 kV line to Connah's Quay with emergency interconnection between the two lines at Ffestiniog. No circuit-breakers will be used on the 275 kV side at Ffestiniog, but connection of the lines and the emergency interconnection will be effected by motor-driven isolators of A.E.I. Switchgear Division manufacture. These isolators are for off-load duty only and are not suitable for switching the magnetising current of the transformers.

Standard forms of protection will be used covering the machines and generator transformers and each machine will be earthed through a 200 Ω wound resistor supplied by the Fawcett Preston Co., Ltd. The Magnestat automatic voltage regulation equipment, which is being supplied by the A.E.I. Electronic Apparatus Division, consists of a magnetic amplifier working in conjunction with the main and pilot exciter, coupled to a motor-driven amplidyne to give a buck and boost control. A compounding system between the automatic voltage regulators will be used to ensure the division of wattless load between the machines.

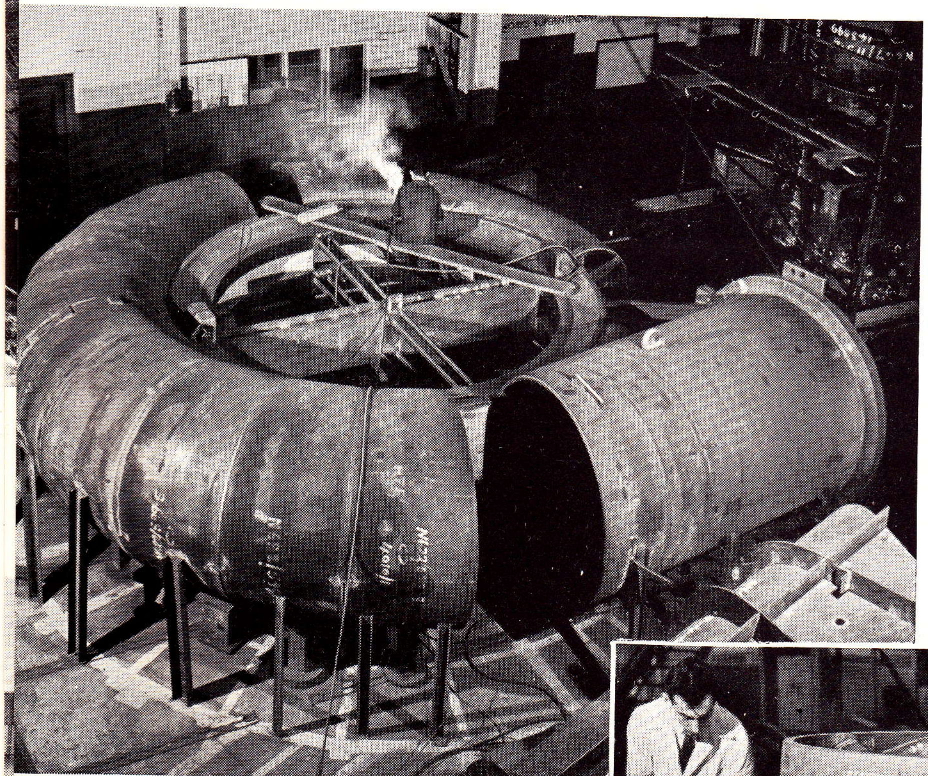
Reyrolle type H distance protection is to be applied to the 275 kV overhead lines, using a carrier acceleration intertrip. The line traps in this equipment are being supplied by the General Electric Co., Ltd.

A set of synchronising apparatus is being supplied for each pair of sets. The automatic synchronising system will be so arranged that all four sets can be started at once and the first of each pair of machines to reach synchronous speed will claim a synchronising system. When this set has been synchronised, the system will automatically be made available for the other set.

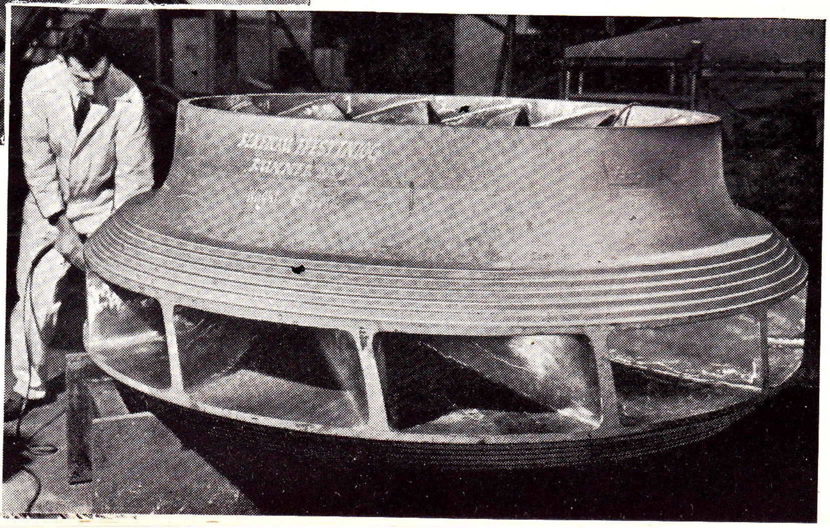
There will be two station auxiliary transformers rated at 1 MVA, 16 kV/415 V, and supplied by Ferranti, Ltd. The high-voltage side will be connected into the centre panel of the 16 kV switchgear already mentioned, so that there will be one transformer for each of the two pairs of sets. These transformers will provide the normal supplies to the main low-voltage distribution boards and will also serve as earthing transformers for the main units. Two 1 MVA transformers will also be supplied and connected to the local Merseyside and North Wales Electricity Board network for standby duty, one for each of the main distribution boards.

In addition, there will be an emergency service distribution board supplied by a 200 kVA automatic starting diesel-driven self-regulating alternator. This board will also allow interconnection of the two main low-voltage distribution boards in the case of failure of normal and standby supplies to one of these boards. The emergency services are mainly intended for the drainage pumps, to prevent flooding of the station.

The main 110 V station battery for essential and emergency services is being supplied by Chloride Batteries, Ltd. It consists of 54 Planté cells, type HHPW16, assembled in lead-lined wood containers,



Above: Final stage of fabrication of turbine spiral casing and speedring at the 'English Electric' works at Netherton



Right: No. 1 turbine runner being ground

and has a capacity of 960 Ah at the 10-hr rate at 60°F. Special features incorporated in the design of this battery result in a lower internal resistance as compared with conventional batteries. This increases the efficiency at high rates of discharge enabling it to perform the same duty as a conventional 1,600 Ah battery. The battery will be required to supply a continuous load of 5 A for control devices and circuit-breaker closing and tripping. In an emergency, the battery will also supply lighting (40 A for 2 hr) and feed the bearing oil pumps (for five minutes before shutdown).

Power will also be supplied to the lower dam for the operation of the discharge regulators and to the upper dam for the automatic operation of the motor-wound intake gates. These gates will be solenoid tripped and closed under gravity. Separate batteries will be installed in the northern valve house at the lower dam and in one of the intake towers of the upper dam for the emergency operation of the discharge regulators and intake gates respectively. Duplicate power and signal cables will be provided for the intake gates at the upper dam.

Operation

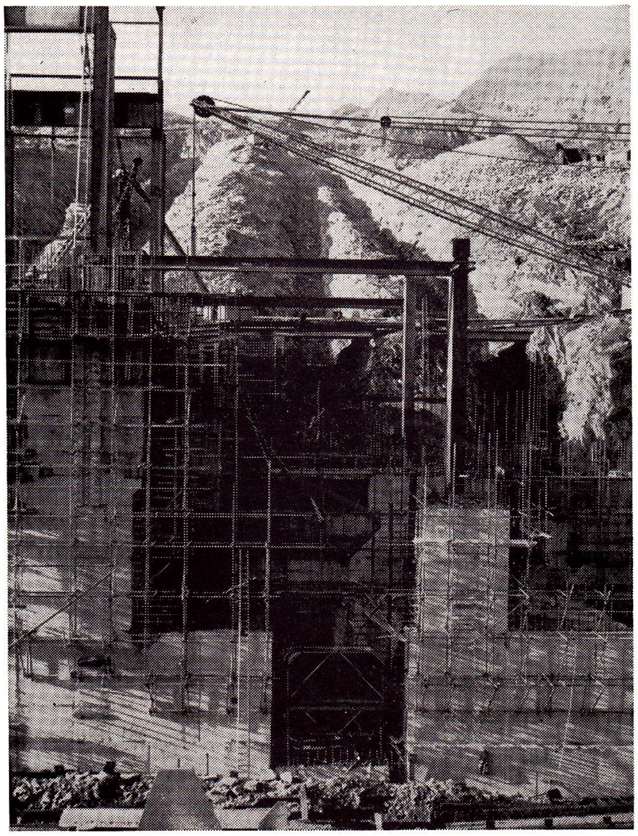
The operation of the station is particularly interesting because of its dual function and the use of automatic stopping and starting sequences. The grid control centre at Manchester will notify the Ffestiniog control room a short time before the station is required to operate and will energise the 275 kV lines at Connah's Quay. The main transformer cooler will start immediately the line is energised and the supply to the main low-voltage distribution boards will be automatically changed over from Area Board supply to the station auxiliary transformer which will have been energised.

Normally each machine will be started and stopped automatically by single pushbutton control from the station control room where loading operations will also be carried out. Three separate pushbuttons will initiate stopping and starting sequences for generating or motoring. Corridor type gauge boards are to be provided at each set and these will include manual control switches for testing purposes. If the automatic control fails, or for any other reason, the stopping and starting operations could be carried out manually at the gauge boards. " Emergency Stop " pushbuttons will also be included on the gauge board. The system is designed so that, if justified in the light of operating experience, the whole station could be remotely controlled from Trawsfynydd.

Generating.—When the station is required to generate, the operator will check that the control selector switch is in the " Automatic " position and the " Ready for Turbine Start " indication is energised. This indication checks that various essential conditions are fulfilled, e.g. that the brakes are released, governor oil pressure is normal, etc. The operator will then press the " Start Generating " pushbutton.

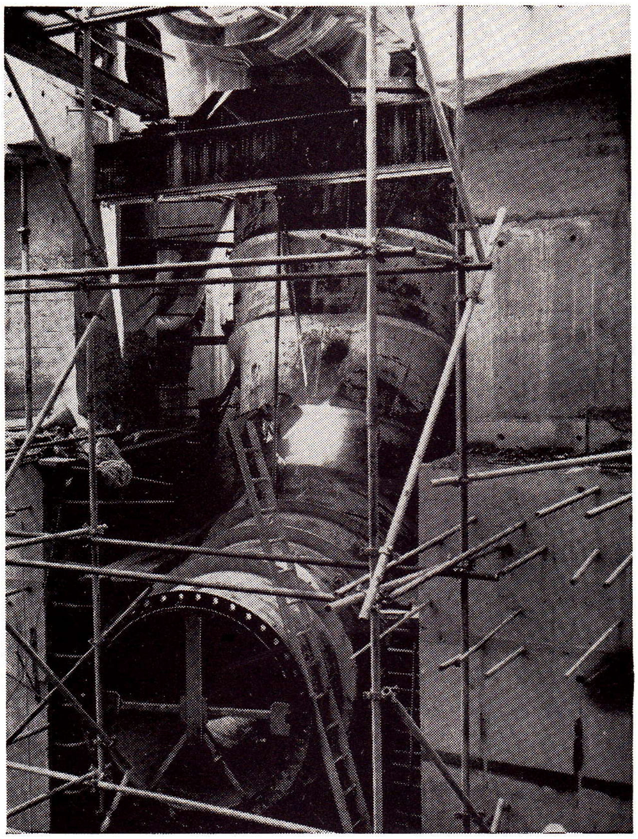
The operation of the " Start Generating " pushbutton will initiate a complicated automatic sequence which will start the essential auxiliaries, open the turbine valve, start the turbine by opening the guide vanes and, when the turbine reaches the correct speed, synchronising will be automatically carried out and the 16 kV breaker closed.

The full automatic sequence will be commenced by



The power station from the east showing No. 3 pump intake and the penstock excavations

No. 3 storage pump intake from inside the station at basement level. The storage pump has a double entry, the top entry can just be seen at the top of the picture



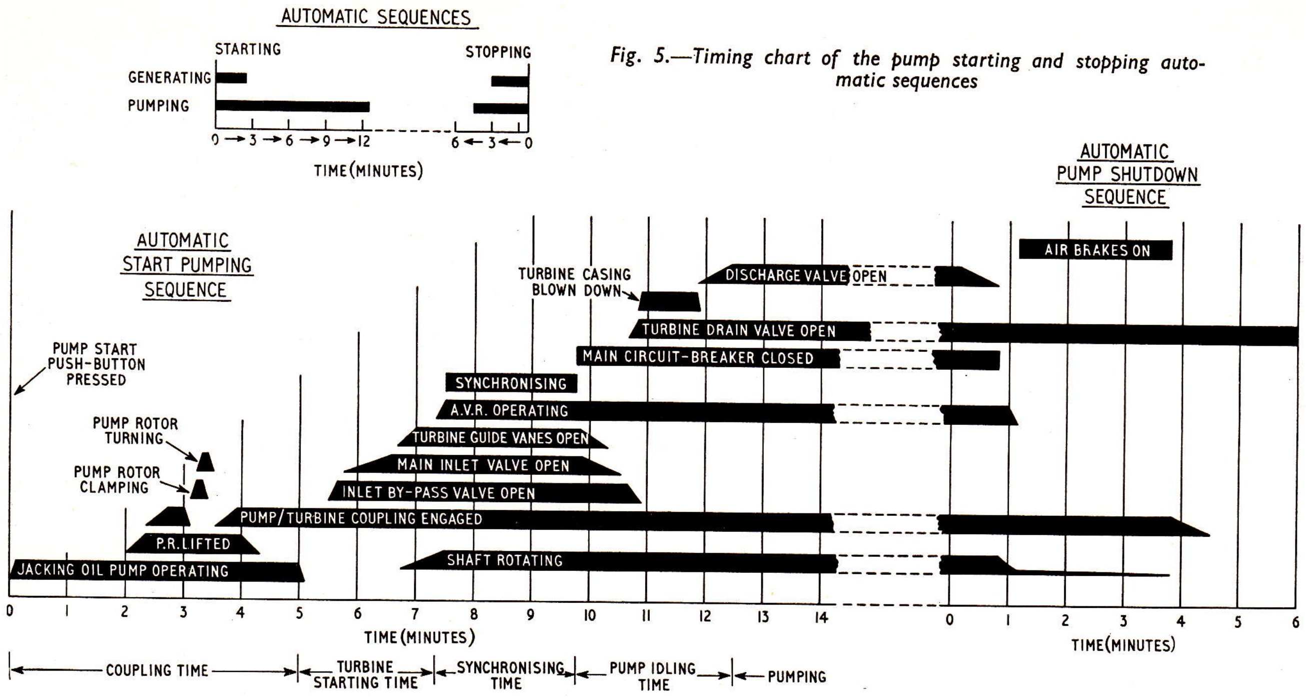


Fig. 5.—Timing chart of the pump starting and stopping automatic sequences

the closing of the turbine master relay which will energise the control circuit busbars and start the turbine and alternator main auxiliaries, comprising the lubricating and cooling water pumps. The turbine main inlet valve by-pass valve will then be operated by a solenoid-operated valve which will allow the penstock water pressure to be applied to the by-pass valve, thus opening it. After the priming of the turbine casing, another solenoid will operate a valve which will release the water pressure on the main inlet valve seal and the seal will deflate. Thereupon a further solenoid will operate the main inlet valve servo-motor by a distribution valve which, in turn, will open the inlet valve.

When the main inlet valve has fully opened, the seals will again inflate. The governor oil admission valve will then be opened and the load-limiting device in the governor will move to the 20 per cent opening position. Pressure oil from the governor circuit will operate the guide vane servo which will open the turbine guide vanes accordingly. The set will then run up to full speed and the automatic synchroniser will cut in and close the 16 kV circuit-breaker when synchronism is established. The a.v.r. amplidyne set will run up to speed and the a.v.r. will take over control. The load limiter will then automatically advance to 100 per cent setting and the operator will adjust the speeder motor and excitation controls to give the required loading. Two overall time check relays will be provided. One will initiate a shut-down sequence if the turbine starting sequence is not completed within a predetermined time. The other relay will cause shut-down if synchronising is not completed within a further given time.

Stop Generating.—To stop generating, the operator will unload the set by operating the speeder motor, thus closing the guide vanes. He will then press the "Stop" pushbutton to initiate the automatic stopping sequence. The turbine master relay will trip, the 16 kV circuit-breaker will open and the governor oil admission valve will close. The main inlet valve seal will deflate, the main inlet valve will close and its seal will inflate. As soon as the set has reached 25 per cent speed, the air brakes will be applied. This is to ensure rapid deceleration while the oil films in the thrust bearing are reduced by the low speed.

When the set is at standstill, the lubricating and cooling water pumps will stop and the brakes will be released. The operator will then notify the group control centre and the 275 kV line will be de-energised and the supply to the main low-voltage switchboards will be automatically changed to Area Board supply. Shut-down after generating will take approximately three minutes and an overall timing relay will give an alarm if the stopping sequence is not completed in this time.

Pumping.—To start a machine for pumping operations, the main transformer will be energised as above and the operator will check readiness to start pumping, which will be indicated by a lamp, provided various conditions are satisfied. These will include checks that the pump suction gates are removed, the upper and lower reservoir levels are correct, the turbine inlet valve is closed, the pressure in the coupling oil receiver is correct and the pump lubricating oil tank inlet valve is open. The operator will then make sure that the auto/manual control selector is in the "Automatic" position.

The operation of the "Start Pumping" pushbutton will initiate the automatic sequence which will check that the turbine and pump are at standstill and then engage the coupling between the pump and turbine. The turbine main inlet valve and the guide vanes will then open, the set will run up to full speed and synchronise, the circuit-breaker will close automatically and the turbine guide vanes and main inlet valve will also close. The machine will now be motoring. The water level in the turbine casing will be depressed and the pump discharge valve will be opened.

The full automatic sequence, which will commence by closing the pump master relay, is diagrammatically represented in Fig. 5. The pump lubricating, cooling

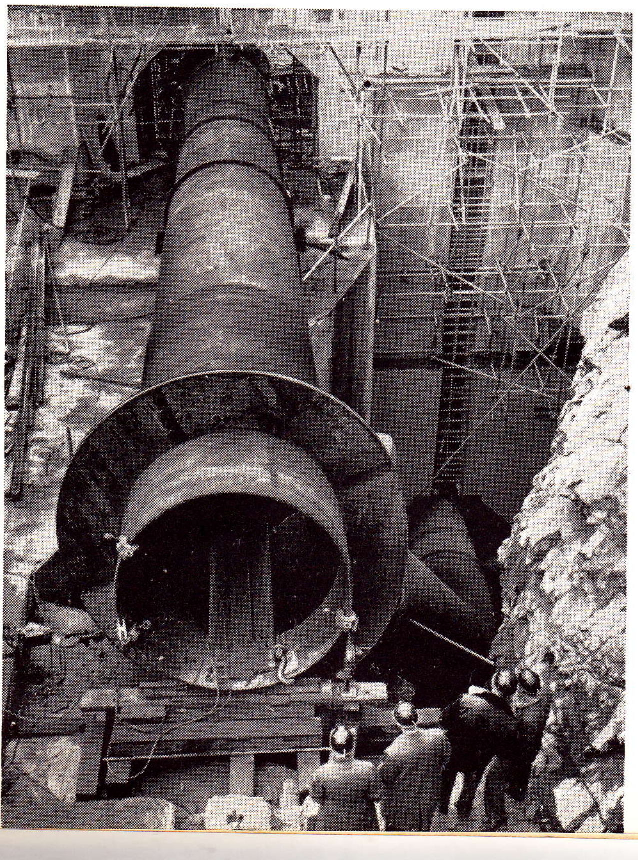
water and jacking pumps will start and the pump and turbine standstill check devices will operate. Each standstill check device consists of a solenoid-operated probe with a rubber tip which will be pressed against the shaft and, if the shaft is rotating, will collapse and move forward towards the shaft, opening contacts which will stop the automatic starting sequence.

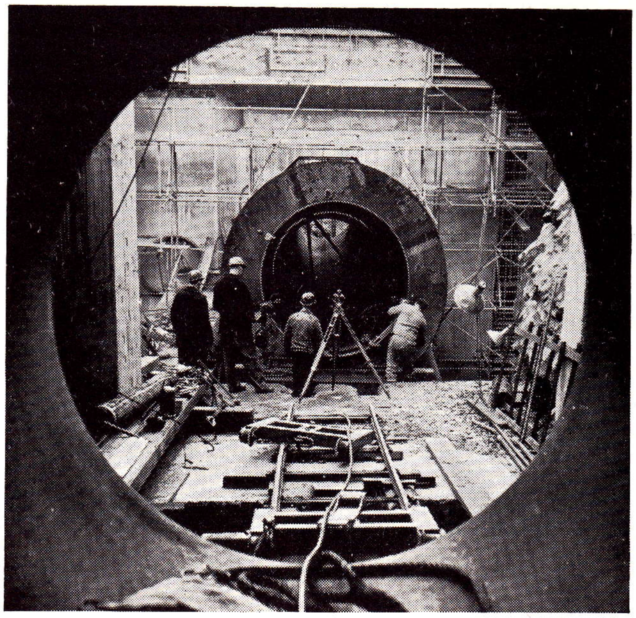
Provided both shafts are stationary, the automatic sequence will continue. A valve will open and allow the jacking oil to enter a cylinder and lift the pump rotor. As soon as the rotor has lifted, the coupling engagement time check relay will start operating and the coupling mechanism will begin to lift the coupling between the pump shaft and turbine shaft.

The coupling will be in constant mesh with teeth at the top of the pump shaft and, when in the lifted position, will be engaged with teeth at the bottom of the turbine shaft. If the coupling fails to engage on its first operation, the pump shaft will be automatically turned and the coupling operation will be repeated under the control of the coupling engagement time-check relay (see Fig. 4). As soon as the coupling engages, the coupling rod will be locked in position, the pump rotor will be lowered and the jacking oil pump will stop.

The turbine starting sequence will then commence operation and the turbine master control relay will be energised. The same sequence, as already described for the " Start Generating " operation, will then take place until the main inlet valve and governor oil admission valve open. The load limiter will then run to a position permitting 50 per cent opening of the guide vanes instead of the 20 per cent opening for the " Start Generating " operation. The turbine guide vanes will follow accordingly and the set will run up to synchronous speed; then the automatic synchroniser will cut in and close the 16 kV circuit-breaker when synchronism is achieved. The a.v.r. amplidyne will run up to speed and the a.v.r. will take over control. At the same time, the turbine guide

Penstock bifurcation. The top pipe leads to the turbine inlet and the lower branch to the storage pump discharge





View from the penstock looking towards the power station. The bifurcation to the storage pump discharge occurs just after the collar face and descends to the right

vanes will be closed by the load limiter which will run to zero and the alternator will then be operating as a motor. The main inlet valve seals will deflate, the main valve will close and the seal will re-inflate. Closure of the main inlet valve will cause the spiral casing automatic drain valve to open.

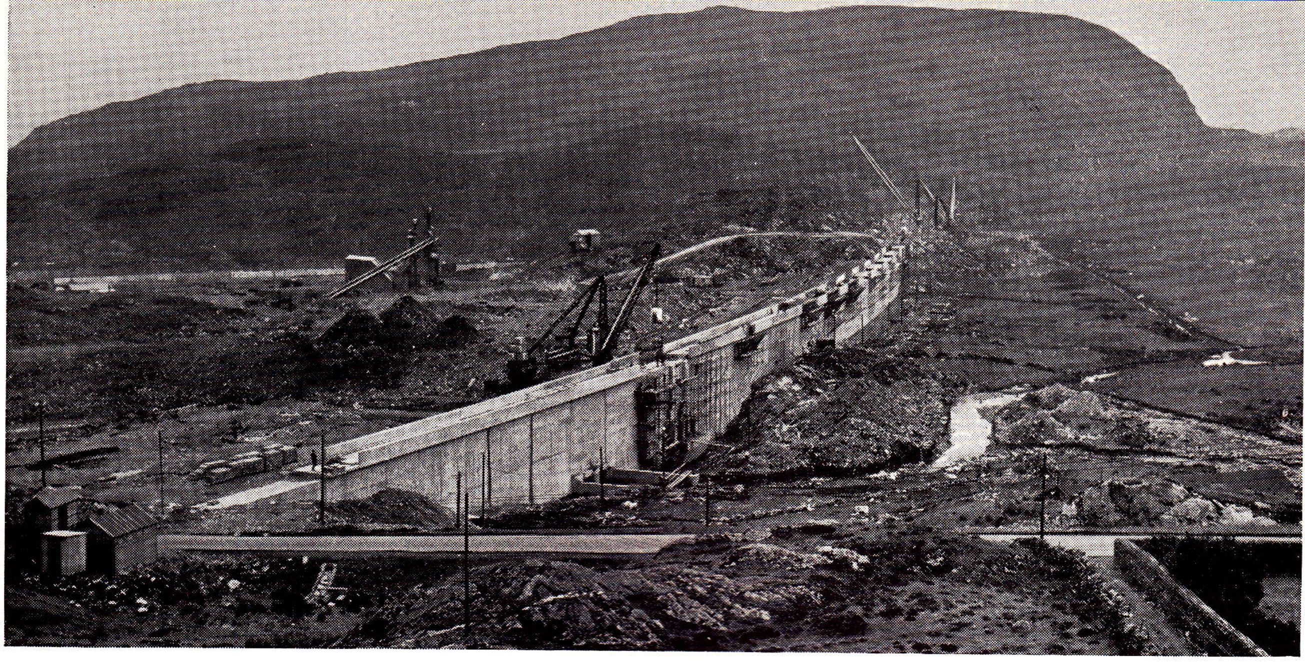
As soon as this valve is open, the air admission valve for blowing-down the draught tube will be operated by a solenoid. This operation will depress the water level in the turbine draught tube so that the turbine runner will be rotating in air. Even though the water will have been removed from the draught tube, a certain amount of air friction will occur and the turbine runner sealing labyrinths would tend to become overheated. This will be prevented by water being sprayed on to the runner seals when the set is operating as a pump or synchronous condenser.

When the blowing-down of the draught tube is completed, the pump discharge valve will open and the pump leak-off valve will close. The pump will now be passing water from the lower to the upper reservoir. The total time from operation of the " Start Pumping " pushbutton of the automatic sequence to the point at which the pump will actually be pumping water to the top reservoir will take about 12½ minutes.

A shut-down will be initiated by sequence time-check relays if (a) the coupling has not been engaged within a predetermined time after pressing the " Start Pumping " pushbutton, (b) the turbine has not run up within a certain time after coupling engagement, (c) the circuit-breaker has not closed within the given time after the turbine has run up, (d) the pump discharge valve has not opened within a certain time after the turbine has run up.

As soon as the automatic starting operation is completed, the operator will adjust the excitation by hand giving the required MVAr loading.

Stop Pumping.—To stop pumping, the operation of the " Stop " pushbutton will de-energise the turbine and



Tan-y-Grisiau dam from the north. The upper reservoir will be on the right-hand side of the picture

pump master relays. The pump discharge valve leak-off valve will open and the pump discharge valve will then close. The pump will then be circulating water to and from the lower reservoir. As soon as the pump discharge valve is fully closed, the 16 kV circuit-breaker will open and the set will begin to slow down.

When the set has reached 25 per cent speed, the air brakes will be applied and, when the set reaches standstill, the turbine, alternator and pump auxiliaries will stop. The brakes will then be released and the coupling will be disengaged. The operator will then notify the group control centre and the 275 kV line will be de-energised. Shut-down after the pumping operation will take approximately $4\frac{1}{2}$ minutes.

It will be appreciated that the turbine and main valve control system consists of servo-mechanisms operated by water pressure controlled by solenoids. The solenoids for connecting or disconnecting the power water to these servos will be situated in cubicles at various floor levels. All solenoids will be latched in and electrically controlled. The control system for the pump will be operated by power oil and these mechanisms will be contained in cubicles situated on the pump floor level.

Quick Shut-Down

On normal shut-down the pump discharge valve will close in about 45 sec, the time being determined by water hammer effects. If there is a power failure, however, closure will be accelerated by an emergency quick-acting device to such an extent that the door performs more than half its stroke in less than 4 sec and is then slowed down to complete closure somewhat more gently in 20 sec.

Alarms

A comprehensive alarm system will be installed which will include conventional alternator and turbine alarms. The pump alarms will also include those dealing with the coupling. Paddle type over and under velocity trips will be installed in each pipeline just below the portal. These will automatically trip the upper reservoir intake gates in the event of a pipeline burst occurring during generating or pumping respectively. Other alarms covering the electrical system and transformer will, of course, be included.

A certain amount of water leakage will take place in the power station and there will be two drainage pumps for each half of the station. These will be operated by level relays situated at two different levels so that one pump will operate when the first level is reached and both pumps will come into operation at the second level. A third level relay, at a higher level, will operate an alarm.

The main consulting engineers to the C.E.G.B. for the scheme are Freeman, Fox & Partners, in association with Kennedy & Donkin for the electrical and mechanical plant, and James Williamson & Partners are responsible for the upper reservoir, intakes, vertical shafts and tunnel works. The architects are Clifford, Tee & Gale. The British Hydrodynamics Research Association and the Hydraulic Research Station of the Department of Scientific and Industrial Research have undertaken experimental work on the intakes and vertical shafts and on the lower reservoir respectively under the supervision of the main consulting engineers.

The main plant contractors are:—Generator/motors, Associated Electrical Industries, Ltd.; water turbines, pumps, valves and coupling, The English Electric Co., Ltd., in association with Sulzer Bros. (London), Ltd.; generator transformers, Ferranti, Ltd.; 16 kV switchgear, the General Electric Co., Ltd.; 275 kV isolators, A.E.I., Ltd.; automatic control system, The English Electric Co., Ltd.

The main civil contractors are:—Stwlan dam, pressure shafts and tunnels, the Cementation Co., Ltd.; power station, penstock foundations and Tan-y-Grisiau dam, Sir Alfred McAlpine & Son, Ltd.; steel linings for two of the tunnels, Redheugh Iron & Steel Co., Ltd.; steel penstock pipes and steel linings for the other two tunnels, Sulzer Bros. (London), Ltd.

Acknowledgment is due to the consulting engineers and the various main contractors for invaluable assistance in the preparation of the text and graphic illustration, and to the chief project engineer of the Northern Project Group of the Central Electricity Generating Board, Mr. W. H. C. Pilling, for permission to publish this article.

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